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STOŽE LANDSLIDE – A CASE HISTORY

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ABSTRACT

The paper describes the Stože landslide that occurred in western Slovenia in November, 2000. It presents the landslide particularities and laboratory tests results. A numerical analysis of the slope failure was performed. It indicated the important role of the ground water level, and the dependence of slope stability upon it. Special laboratory equipment, a large-scale shear cell, was constructed in order to test the landslide material and to indicate the roles of the water content and loading velocities on the residual shear strength of material. A testing method is presented. It was assumed that the behaviour of material with a grain size of 4 mm or less could indicate the general behaviour of the landslide. Taking into account the possibility of an earthquake occurring in this region, attention was paid to the behaviour of this material at very small strains, and to the effect of different water contents and densities of the material. The deformation characteristics of reconstituted samples were investigated in a resonant column test at IST, Lisbon. Showing the influence of the water content and confining stress, empirical equations defining the small strain shear modulus have been proposed for different water contents.

INTRODUCTION

The very severe landslide that occurred in Slovenia in November 2000 attracted the attention of the entire country and also opened up some new technical questions. Sudden movements of soils and rocks under the influence of gravity seem to be mostly induced by rainfall or some other cause of ground water level change. The described landslide occurred in a seismically very active area. Although at the moment when the landslide was triggered, no earthquake was recorded, it is probable that some cracks in the landslide area were caused by ground movements due to past earthquakes. Combined with heavy rainfall, these cracks could have permitted for ground saturation. The landslide material consists of fines and gravel whose grain sizes make it impossible to test it in a simple shear cell. Special laboratory equipment, a large-scale shear cell, was therefore constructed in order to test the landslide material. The testing method is presented. The results indicate the roles of water content and loading velocities on the residual shear strength of material.

The deformation characteristics of the landslide material at very small strains were investigated in a resonant column test. The results were combined with those of field test measurements. The case was analysed numerically for different water levels using the commercially available finite difference program FLAC and the assumption that the material has no liquefaction potential.

THE STOŽE LANDSLIDE

History of the landslide

Continuous rainy weather affected the western part of Slovenia in autumn 2000. On November 15th, 2000, a mass of moranic material and slope gravel began to move near the Mangartski potok gorge. The area is known as Stože (1340 – 1580 m a.s.l.) and is situated below Mount Mangart in the western part of Slovenia. The mass damaged the Mangart local road (Bovec-Predel) and moved down to the Predelica ravine, where it dammed up the stream of the Mangartski potok at an altitude of 1250 m. The accumulation was about 10 m high and it was deposited over a 1450 m length of the Mangartski potok stream. As a consequence of extremely heavy rainfall, a second - major slide occurred on the slopes of Mount Mangart in the early morning of November 17th, 2000. The mass reached the water collected behind the first landslide and saturated itself there. In a few hours it transformed into a debris flow - a mixture of water and soil. The flow moved along the bed of the Predelica and reached the village of Log pod Mangartom (Oštir et al 2001). The velocity of the flow was estimated to be between 8 and 15 m/s.

Some facts about the landslide

- The area of the second failure, the actual debris flow, was estimated to be about 25 hectares of forest
- Its width was about 300 m, and it was 1.5 km long and up to 50 m thick

- Approximately 1,500,000 m³ of material was moved
- The ground level during the landslide was lowered by up to 40 m in some places, and rose by to 20 m in others
- Two bridges, as well as several residential and industrial buildings, were destroyed
- Seven people died
- About 3,000,000 m³ of unstable material remained in the landslide area, representing a potential danger of landslide recurrence

Geology

Geological mapping of the landslide site proved the existence of very good geological reasons for the triggering of the landslide. The mountain ridge west of Mount Mangart is mainly composed of massive Upper Triassic carbonate, which is partly interrupted by clastic rocks and some poorly permeable Carnian Calc stoneware. (Oštir et al 2001) The base of the landslide forms a block of poorly permeable carbonate-clastic strata situated between blocks of massive and bedded dolomite. Glacial sediments rich with silt were deposited over stepped bedrock and dolomite gravel in the Pleistocene.

The event occurred at an altitude of 1525 m, in glacial sediments - moraine and slope debris, which covered tectonically highly-fractured dolomite overlying impermeable layers of marly limestone (Petkovšek B 2001). Dolomite is an excellent aquifer, and during heavy precipitation the water level in the rock rises substantially, saturating the overlying soils, rich in clay, with water. The exact water level at the moment of the beginning of the slide is not known. An estimate was made using a back analysis.



Fig. 1. The Stože landslide

MATERIAL PROPERTIES

Static properties

Several laboratory and in situ tests were performed in order to obtain the static properties of the material (Majes et al 2001). A preliminary back analysis of the slope failure was performed, with the aim of confirming the results of the laboratory and on-site defined static properties of soil, see Table 1.

Table 1. The constitutive parameters of the Stože landslide material (Majes et al 2001)

Soil layer	γ [kN/m ³]	γ_{sat} [kN/m ³]	E [MPa]	ν	c [kPa]	ϕ [°]
Moraine ¹	22	23	50	0.3	20-30	36-38
Gravel ²	22	23	100	0.3	5	42
Landslide ³	19	20	110	0.3	0.5	33
Bedrock ⁴	25	25	1000	0.3	500	50

- ¹ silty-clay glacial moraine with limestone gravel
- ² dolomite gravel with rock inclusions
- ³ landslide material with fine grained gravel
- ⁴ dolomite bedrock

Tested material and samples preparation

In the case of the Stože landslide the expert group assumed (Majes 2001) that the Lacustrine carbonate silt, clay and moraine fines, with grain sizes smaller than 4 mm, in the sliding material could lead to the general behaviour of the landslide during the sliding. Therefore two different testing procedures were performed. The goal of the first one was to define the effective shear strength of the material and its dependence upon the velocity of sliding and the moisture content. The large-scale shear cell tests were performed in the laboratory. The landslide material, including grain sizes up to 45 mm, was tested in that case.

The other kind of test, was the resonant column test. The goal of these test was to find out the dynamic properties of the fines. In order to evaluate the equivalent shear modulus and damping ratio, tests were performed on reconstituted samples made of natural material grain sizes smaller than 4 mm.

Reconstituted samples for both series of tests were prepared by means of wet tamping with the objective of achieving moisture contents and densities similar to those occurring naturally. The grain size distribution curves are presented in Fig. 2.

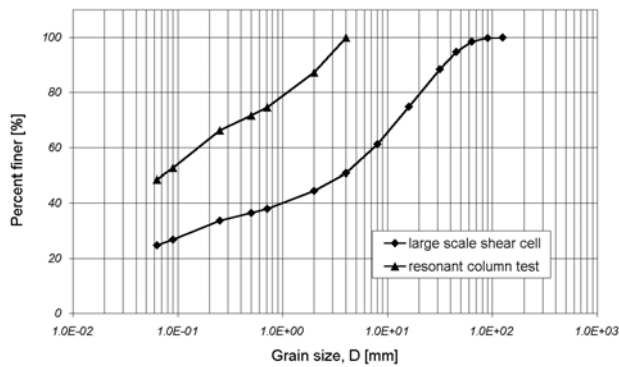


Fig. 2. Gradation curves

Dynamic characterization

The large-scale shear cell testing method. A large-scale shearbox, was constructed in order to test the landslide material, including grain sizes up to 45 mm in means to control the effective shear strength of the material and its dependence upon the velocity of sliding. Use of a shearbox of this size made possible to measure the pore water pressure. The shearbox incorporates a special hydraulic loading system, which controls the rate of displacement.

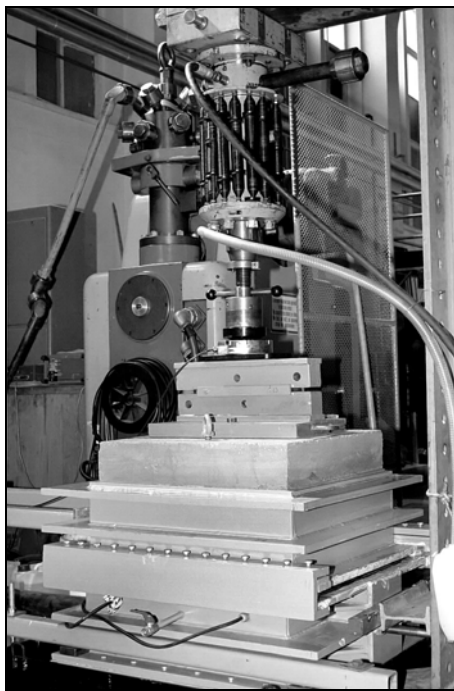


Fig. 3. The large-scale shear cell during the test

The large-scale shear cell apparatus consists essentially of components similar to those of the standard (small) shear cell except that they are on a larger scale. It comprises a drive unit with a loading piston, a shear cell assembly and, as a difference to the standard shear cell, a pore pressure transducer facility is included.

A split box with inner dimensions 630 mm × 630 mm is used. The lower fixed part of the box is 230 mm high. It is filled during the test to 140 mm high with a saturated porous material through which draining is achieved. A specimen with a height of 180 to 205 mm is positioned above this layer. The specimen is impermeable covered at the top to prevent draining in the vertical direction and is supposed to be subjected to shear under a certain vertical load applied by a hydraulic piston. Two valves in the bottom part of a shear box are used to determine whether drainage, i.e. a change in water content, is permitted during the test.

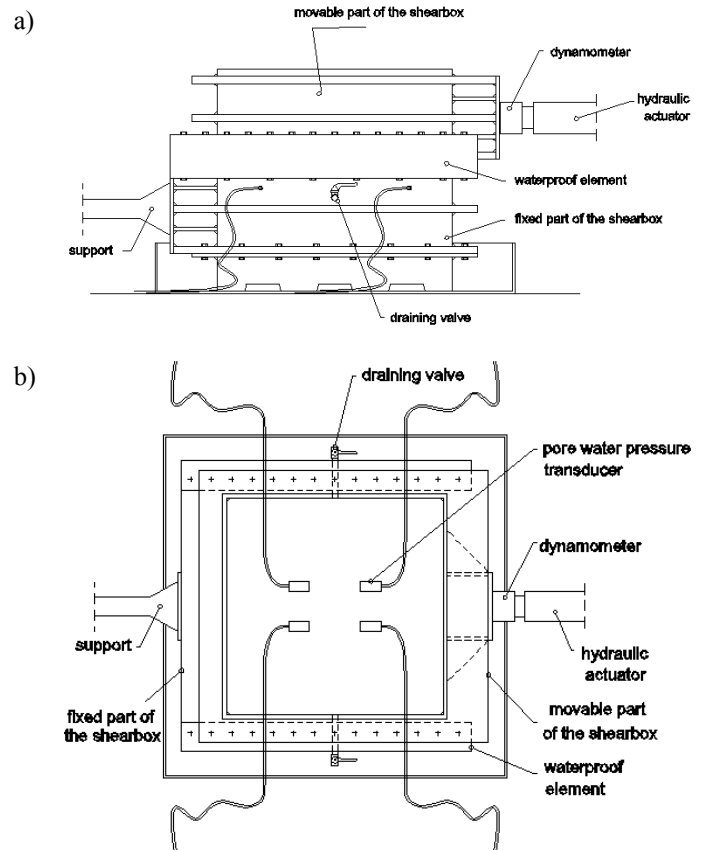


Fig. 4. Arrangement of a large-scale shear cell: (a) cross section, (b) plan view

The shear load is applied by a hydraulic piston with a capacity of 160 kN and capable of applying displacements moving amplitudes of ± 125 mm. Another hydraulic piston, which can provide up to 200 kN provides the normal loading system. The upper and bottom parts of a box are fixed together in the longitudinal direction with special waterproof elements covered with Teflon on a sliding plate. The sliding plates are waterproofed in the transverse direction. A rubber washer and impermeable fat make this possible. Pore pressure transducers built into the specimen measure the pore water pressure in the specimen during the test. Two of them are installed above the surface of sliding and two of them are installed under it. The

friction between the two parts of the box is measured before the test at different strain rates. The results of the shear test are corrected by this value. Reconstituted samples of material from the Stože landslide were used in the tests. They were all prepared by means of wet tamping at moisture contents of 11-12 and 15-16 %. The samples were subjected to constant normal stresses of 10, 50 and 100 kPa. The tests were performed at different strain rates: 1, 2, 4, 6 and 8 mm/min, respectively.

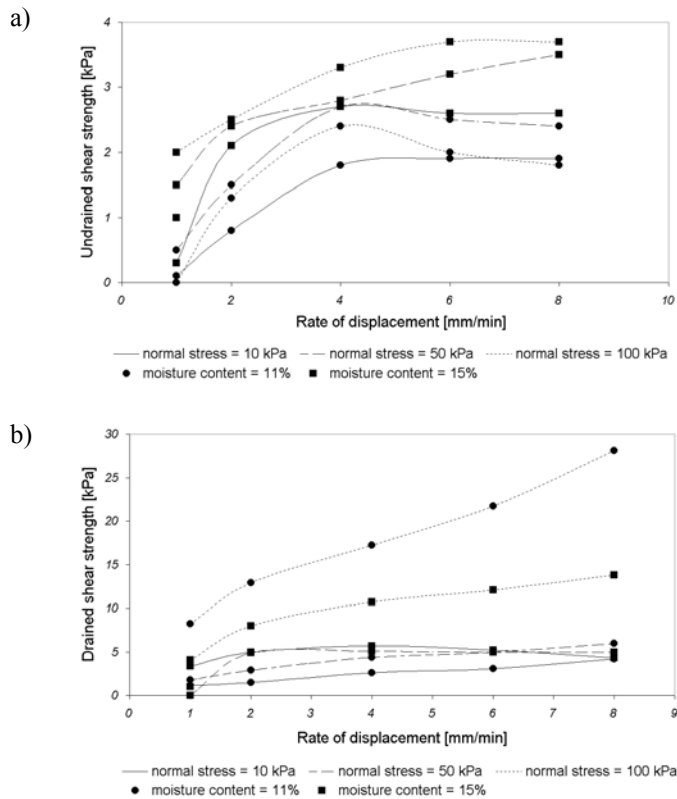


Fig. 5. Variation of residual shear strength with strain rate at different moisture contents and normal stresses: (a) the undrained shear tests, (b) the drained shear tests

The results indicated the dependence of shear strength upon the rate of displacement and the moisture content. It is evident that the shear strength increases with an increase in normal stress. Drained conditions during the test cause an increase in shear strength. Shear strength also increases with an increase in the rate of displacement (Fig. 5). Figure 6b shows how the value of the drained shear strength depended upon the moisture content. It is evident that with increasing moisture content the drained shear strength approaches a certain value, no matter the normal stresses.

The resonant column tests. A series of resonant column tests were performed at IST, in Lisbon. The apparatus which was used in the case of the presented tests was of the fixed-free type. It is fixed at its base and excited in torsion at the top. The top end is vibrated in torsional mode by means of an electromagnetic drive system (SEIKEN model DTC-158). The

tested reconstituted specimens were solid cylinders, 7.0 cm in diameter and 10.0 cm in height. They were prepared with materials (Fig. 2) having three different dry densities: 1.8, 1.9 and 2.0 t/m³. For all the test samples the procedure used to perform the resonant column test was the multi-stage technique, in which magnitudes of effective confining stress of 20, 50, 70, 100, 200, 400, 500 and 600 kPa were applied to the same specimen.

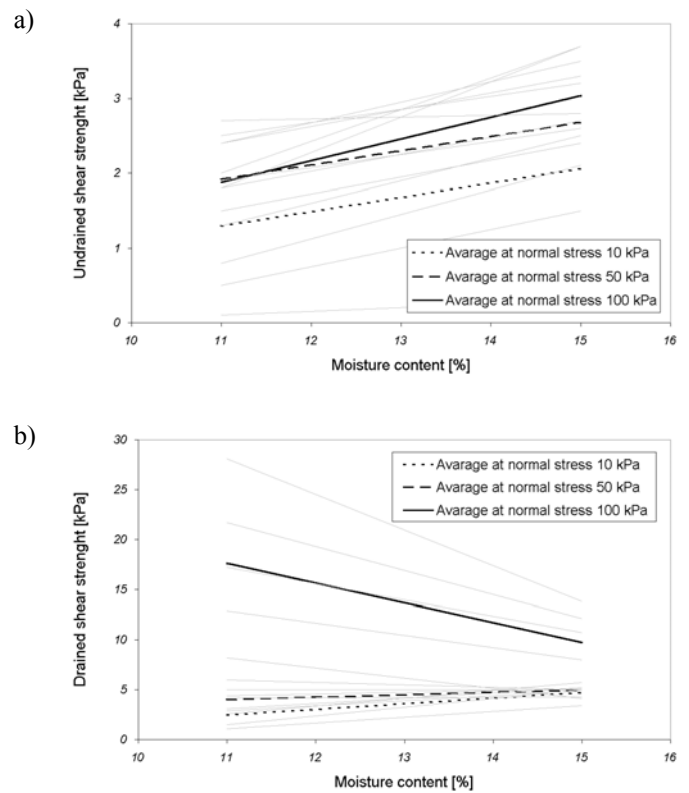


Fig. 6. Variation of residual shear with strain rate at different moisture contents and normal stresses: (a) the undrained shear tests, (b) the drained shear tests

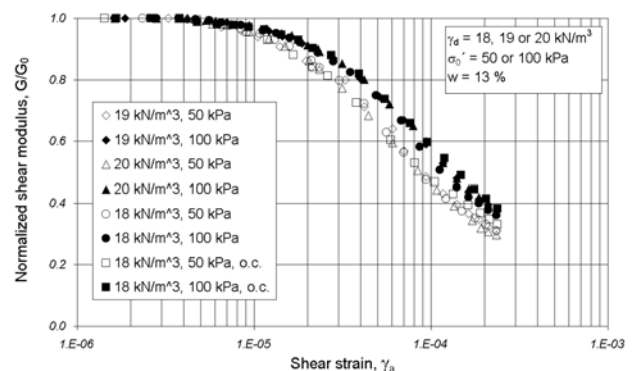


Fig. 7. Variation in the normalized shear modulus reduction curves with density and over-consolidation (o.c. means samples over-consolidated by 600 kPa)

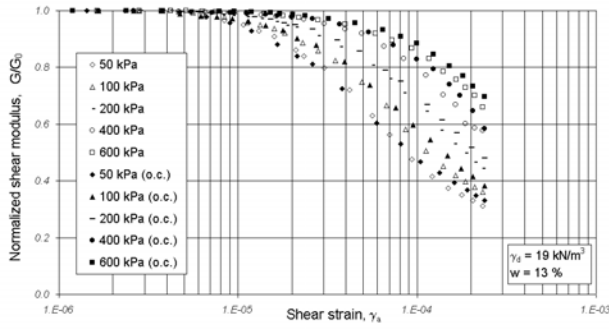


Fig. 8. Variation in the normalized shear modulus reduction curves with effective confining stress and over-consolidation (o.c. means samples over-consolidated by 600 kPa)

Changes in the shear modulus and damping ratio values in the non-linear range were observed. The decreasing of the normalized shear modulus shows non-linear behavior. The strain above which this process starts is called the elastic threshold shear strain and it is estimated at 4×10^{-6} in the cases that this paper presents. Variations in G/G_0 were investigated at various densities and confining pressures. The normalized shear modulus reduction curve did not depend a lot on density for the tested soil (Fig. 7), but it was clearly affected by the effective confining stress as shown in Fig. 8. The G/G_0 versus $\log \gamma$ curves of the tested material were classified for 5 effective confining stress levels by means of normal consolidation and over-consolidation with 600 kPa. The curve moves to the right as the effective confining stress increases. In the case of over-consolidated samples the curve is also a little more right positioned. The damping ratio decreases with increasing confining pressure. The effect of density is insignificant. In general, over-consolidation decreases the small-strain damping ratio.

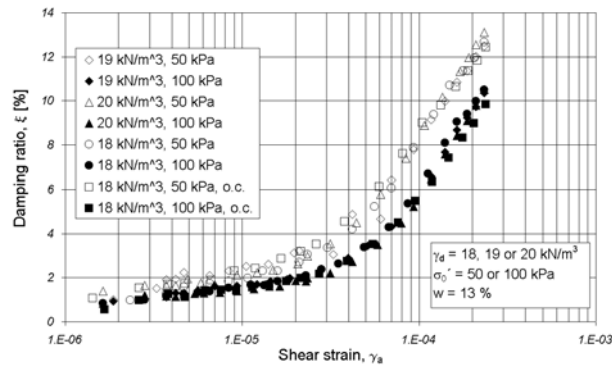


Fig. 9. Variation in the damping ratio with density and over-consolidation (o.c. means samples over-consolidated by 600 kPa)

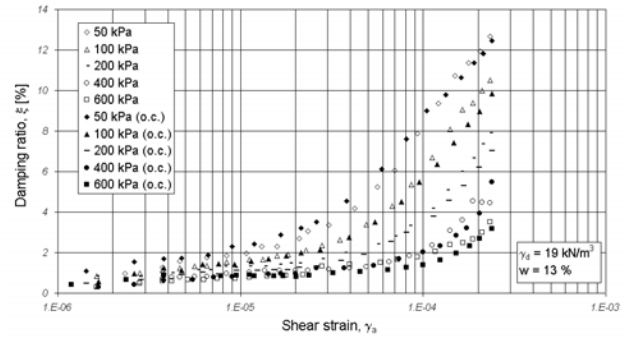


Fig. 10. Variation in the damping ratio with effective confining stress and over-consolidation (o.c. means samples over-consolidated by 600 kPa)

The initial shear modulus, G_0 was measured under different effective confining stresses σ'_0 for various states of packing, represented by different void ratios, e . The general form of the equation (1) was used (Ishihara, 1996; Hardin 1978) to describe this relationship.

$$G_0 = AF(e)(\sigma'_0)^n \quad (1)$$

where A and n are non-dimensional constants; σ'_0 = the effective confining stress; and $F(e)$ = a function that describes the effect of the void ratio defined as (Hardin et al 1963):

$$F(e) = \frac{(2.17 - e)^2}{1 + e} \quad (2)$$

where e = void ratio. Generally, G_0 and σ'_0 (1) are in kPa. The initial shear modulus, G_0 at the end of primary consolidation has been divided by the function $F(e)$ (2) and plotted against the effective confining stress employed in the test. The data points plotted on the \log - \log scale are related linearly and confined in a narrow range. They can be fitted together using the least-squares regression method, and values of the coefficients A and n can be obtained. The same procedure was repeated for three different sample material moisture contents. The empirical equations for the tested material on small strain modulus depending on void ratio and effective confining stress in relation to different moisture content can be defined based on equation (1). The obtained values of the coefficients are presented in Table 2.

Table 2. Constants in the proposed empirical equation on small strain modulus

Moisture content [%]	A	n
7	9600	0.5
10	5300	0.5
13	5100	0.5

It is obvious that the initial shear modulus value depends upon the moisture content. It decreases as the moisture content

increases. This reduction continues until the moisture content is equal to or higher than the optimal moisture content as defined by Standard Proctor test.

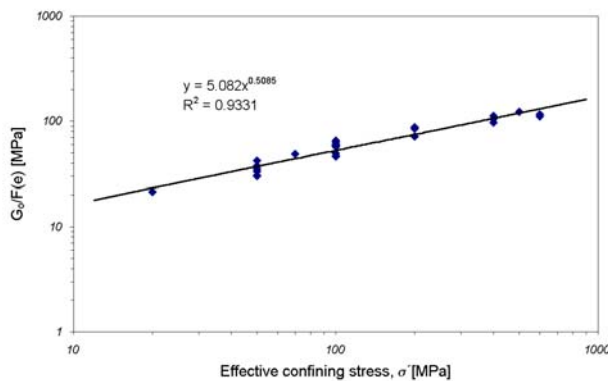


Fig. 11. Initial shear modulus as a function of the void ratio and effective confining stress ($w=13\%$)

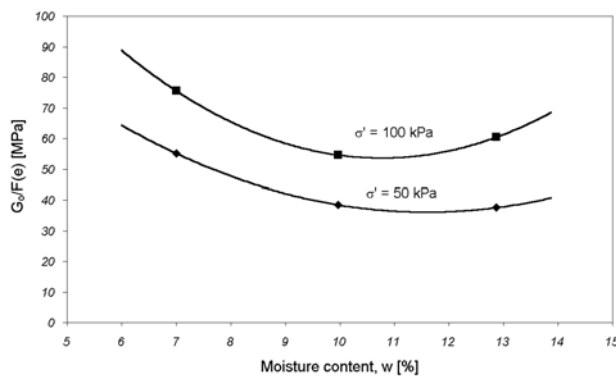


Fig. 12. Effects of moisture content and the effective confining stress on initial shear modulus

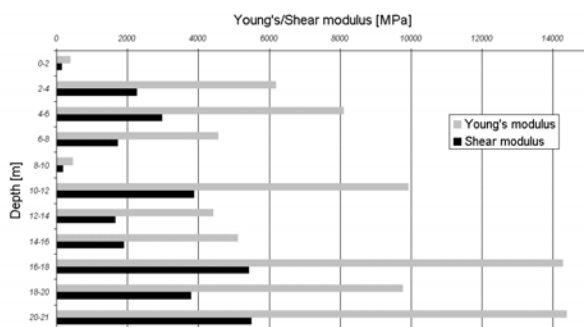


Fig. 13. Young's modulus and the shear modulus obtained by the Down-Hole seismic method (Car et al 2001)

Field test measurements. Seismic wave testing was performed using the down-hole method on the landslide area. The shear wave velocity of the various soil layers was determined by

shooting down the hole, and the moduli were calculated from the obtained values of wave propagation velocities (Fig. 13).

NUMERICAL ANALYSIS

Based on the obtained laboratory test results and other field investigation a seismic analysis of Stože landslide was performed. The results of the dynamic characterization of the landslide material indicated the important role of moisture content. The different ground water levels, and the dependence of slope stability on them, were checked in the numerical analysis. The acceleration records of four different earthquakes which had occurred in the past in the area near this location were used. The effects of seismic loads acting on the slope were analysed numerically using the commercial available finite difference program FLAC.

Landslide modeling

A representative section (Fig. 14) was chosen for the landslide analysis. A mathematical model with 16800 elements was designed. It modeled the landslide to a depth of approximately 130 m. Initially, the geostatic stresses were simulated in the model under elastic conditions. An elastoplastic constitutive model based on the Mohr-Coulomb failure criterion, with strain softening, was then established for all the different layers of the landslide section.

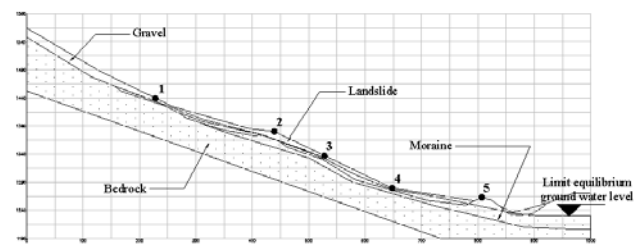


Fig. 14. Representative section of a Stože landslide with five observed points and ground water level at the equilibrium state

Initial pore pressure was estimated from the ground water level, which changed according to different cases in the analysis. It was first verified whether the system with the selected strength parameters with initial pore pressure was in equilibrium in the static phase. The equilibrium state ground water level was found through that. Setting the ground water level below that limit the seismic response of the slope was observed. The mathematical model did not allow any excess pore pressure generation due to cyclic loading as it was assumed that the material has no liquefaction potential.

Seismic loads and responses of the slope

The acceleration records (Fig. 15) for two horizontal components of the earthquake recorded in Monte Negro, 1979,

at Petrovac na moru, and the earthquake which occurred in north Italy, 1976 in Tolmezzo, were used in the numerical analysis.

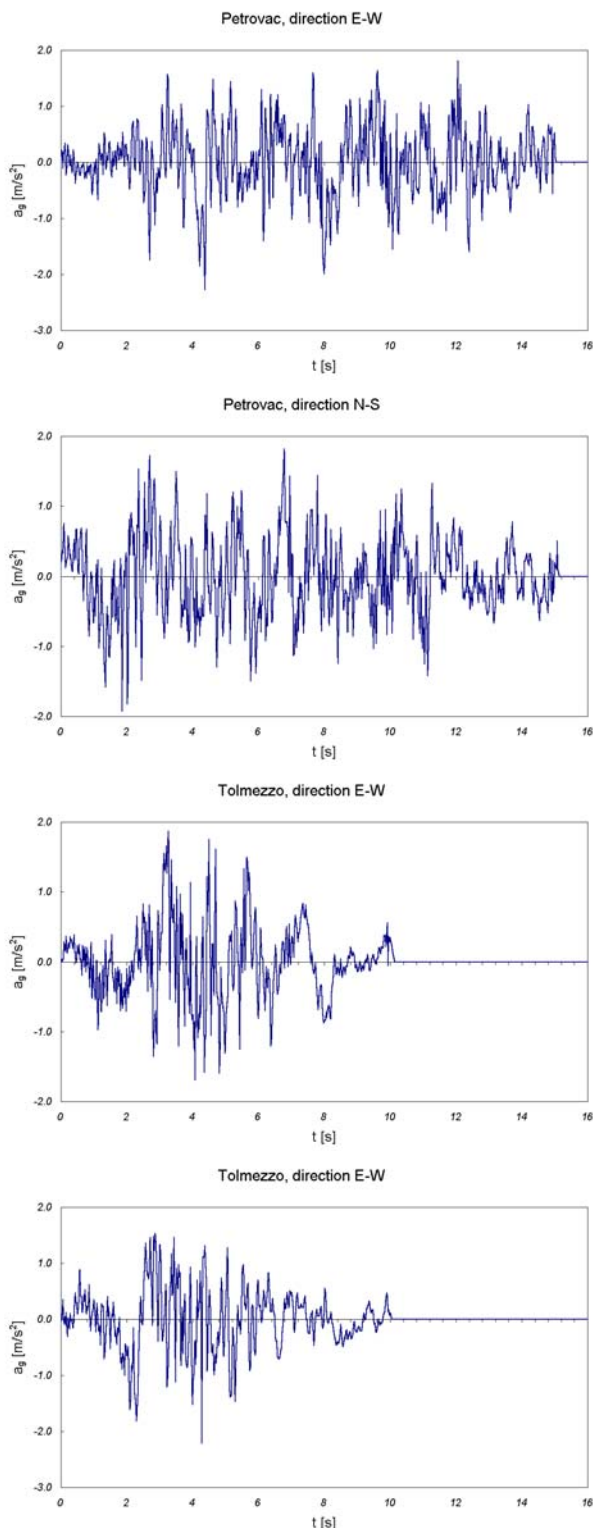


Fig. 15. Acceleration records of the earthquakes recorded in the areas near the landslide location

The average peak horizontal acceleration of the four accelerograms presented above is $0.211g$, where g means ground acceleration. The earthquake acceleration records were applied at the nodes of the bottom boundary. Free field conditions were introduced at the two lateral boundaries of the model.

The seismic response was estimated for the landslide area in the case of the ground water level at the equilibrium state level. The results of the numerical analysis indicate a shear band having a maximum depth of about 10 m in the middle part of the slope. There are small differences in the maximum horizontal displacements. A slight sliding of 3 m average occurs during the earthquake loading and it stops at the end of the loading.

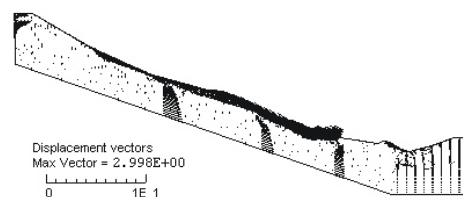


Fig. 16. Typical displacement vectors plot when the trigger of the slide was caused by seismic loads acting (Petrovac EW)

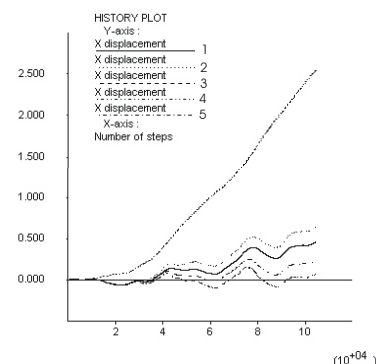


Fig. 17. Typical horizontal displacement at observed points (Petrovac EW)

CONCLUSIONS

The Stože landslide and its particularities are described. The process of landslide stabilization and remedial work included also extensive laboratory tests, which were performed on the landslide material. As the area of the landslide location is seismically very active, the possibility of an earthquake occurrence has been taken into account. Attention was therefore paid to the behaviour of this material at very small strains, and to the effect of different moisture contents and rates of displacements.

Two different laboratory testing procedures were used to determine the dynamic characteristics. Special laboratory equipment, a large-scale shearbox apparatus, was constructed in order to test the material, including grain sizes up to 40 mm. The impact of moisture content and rate of displacement on the material shear strength has been investigated. The results indicate an increase in the material shear strength as the rate of displacement increases. The relations between moisture content and shear strength depend upon draining and stress conditions.

A series of resonant column tests were performed on landslide material with grain sizes smaller than 4 mm in order to investigate the shear modulus and damping ratio values. It was found that at moisture contents lower than the optimal one the initial shear modulus decreases as the moisture content increases. Empirical equations defining values of the small strain shear modulus for three different water contents have been proposed, indicating the influence of the void ratio and confining stress.

It is obvious that the moisture content in the landslide material is one of the most important factors of its behaviour. The important role of ground water level and the dependence of slope stability upon it were also indicated during the numerical analysis of the landslide. Effective draining should be carried out in order to achieve the required safety of the slope. The ground water level should always be below in the numerical analysis determined so-called equilibrium state, at which sliding without any extra load begins. In case of an earthquake occurrence, slight sliding of the slope can be expected. If no liquefaction of the sliding material happens, sliding should be stopped at the end of the earthquake load acting. The liquefaction potential of the landslide material should be estimated in order to prevent any possible disaster in the future.

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